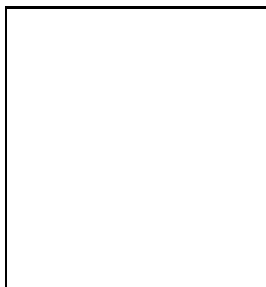


SEARCHES FOR EXOTICA AT LEP

F.-L. NAVARRIA

Dip. di Fisica, Univ. di Bologna, V.le Berti-Pichat 6/2, I-40127 Bologna, Italy
INFN, Sezione di Bologna, V.le Berti-Pichat 6/2, I-40127 Bologna, Italy



The results of various searches for new physical phenomena beyond the Standard Model using data from the four LEP experiments are summarized. Topics presented include the search for flavour-changing neutral currents with single top production, compositeness leading to the production of excited leptons, and manifestations of extra dimensions.

1 Introduction

The Standard Model (SM) works extremely well so far, yet it is believed to be only a low-energy effective theory and new physics beyond the SM is expected to appear. Some of the motivations for looking beyond the SM are neutrino oscillations, the problems related to the unification of forces (hierarchy problem), and the origin of the mass hierarchy. Theoretical prejudices vary a lot, but indicate, in some cases, that the new scale could be as low as 1 TeV. New phenomena could therefore have been accessible with the Large Electron Positron Collider at CERN. LEP was stopped at the end of 2000, after reaching $\sqrt{s} = 209$ GeV, and will be replaced by the Large Hadron Collider (LHC) in 2007. The four LEP experiments, ALEPH, DELPHI, L3, and OPAL, have collected almost 2.4 fb^{-1} of data at the highest LEP2 energies (above 182 GeV). Here several searches for new exotic phenomena will be presented, namely the searches for single top production in Section 2, excited leptons in Section 3, and extra dimensions in Section 4. Many of the final results have been available since some time, but in a few cases the experiments have not yet produced the analysis of the full data sets (in particular the higher energy data) because of lack of manpower, or they are just finalizing the results. A LEP working group was set up to combine the results of the four experiments and obtain the best limits in the search for exotic phenomena. Two combinations were performed in 2001 often using preliminary data¹. A combination of the limits on extra dimensions has been produced recently¹.

2 Single top production

Flavor Changing Neutral Currents (FCNC) are absent in the SM at the tree level and severely suppressed even at the one-loop level. For example, at LEP2 energies the production of a single top quark, $e^+e^- \rightarrow t\bar{c} + \text{c.c.}$ ($t\bar{u} + \text{c.c.}$), is present at the one-loop level in the SM, but the cross-section is expected to be only $O(10^{-9} \text{ fb})$. The SM process is therefore totally invisible and single t production can be used as a probe for new physics. FCNC can also be searched for at HERA via single t production, $ep \rightarrow etX$, and at the Tevatron via rare top decay, $t \rightarrow Z(\gamma) c(u)$, since the one-loop level $\text{BR}[t \rightarrow (Z, \gamma) c(u)]$ is predicted to be $< 10^{-10}$ in the SM. Several extensions of the SM predict enhancements of the single t production cross-sections or larger BRs. FCNC t production and decay can be expressed in terms of anomalous couplings κ_γ and κ_Z ,² with a scale assumed to be equal to m_t . Events of the type $e^+e^- \rightarrow t[\rightarrow b W(\rightarrow q\bar{q}, l\nu_l)] \bar{c}$ or \bar{u}) have been searched for using b -tag and kinematic variables. No excess was found over the SM background and exclusion limits were derived for the production cross-sections. All experiments have now produced final results^{3,4,5,6}. Figure 1 (left) shows as an example the limits published recently by DELPHI⁴: also shown are the limits obtained by ZEUS at HERA^a, and by CDF in Run I at the Tevatron. H1 has produced limits which are looser than those of ZEUS because it has observed an excess of leptonic events at high p_T . However, this excess, is not observed in other channels (hadronic) or by ZEUS. The limits on the anomalous couplings and on the BRs derived from the combined LEP data are shown in Fig. 1 (middle) and Fig. 1 (right): a $\text{BR}[t \rightarrow Zc(u)] > 0.081$ is excluded at 95% CL for $\kappa_\gamma = 0$.¹

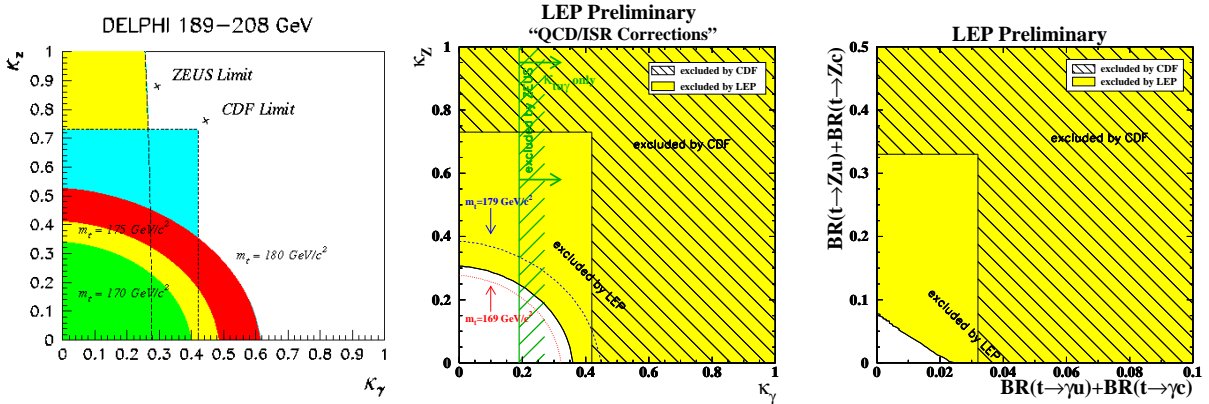


Figure 1: Left: Search for single top production, 95% CL area excluded by DELPHI in the κ_γ, κ_Z plane. Middle and right: anomalous couplings and top BRs excluded by combined LEP data and by CDF.

3 Excited leptons

The existence of three families of quarks and leptons is a strong motivation to look for substructure. In composite models⁷, quarks, leptons and gauge bosons are composite with an associated energy scale, Λ . At $s \ll \Lambda^2$ there could be manifestations of these subconstituents through anomalous decay modes, anomalous electric and magnetic multipoles, excited fermions, leptoquarks and contact terms. For example, excited leptons would decay promptly emitting a gauge boson, γ , W or Z , and an ordinary lepton of the same family. The possible processes are $l^* \rightarrow l\gamma, \nu W, lZ$; $\nu^* \rightarrow \nu\gamma, lW, \nu Z$. BR, topologies and efficiencies depend on the relative

^aThe experiments at HERA are mostly sensitive to $\kappa_{tu\gamma}$, since Z exchange is suppressed owing to the large Z mass and because t is produced at large x . The difference in the ZEUS exclusion limit in Fig. 1 left and middle is due to a factor of $\sqrt{2}$ difference in the Lagrangian used at LEP and HERA: the correct one, from the LEP point of view, is the one in Fig. 1 left.

strengths, f and f' , of the weights multiplying the SM couplings. For instance, if $f = f'$, $\nu^* \rightarrow \nu\gamma$ is forbidden; if $f = -f'$, $l^* \rightarrow l\gamma$ is forbidden. At LEP two classes of processes were investigated: pair production, $e^+e^- \rightarrow l^*l^*, \nu^*\nu^*$, with a discovery limit $m_* \sim \sqrt{s}/2$; single production, $e^+e^- \rightarrow l^*l, \nu^*\nu$, with a discovery limit $m_* \sim \sqrt{s}$. The single production cross-sections depend on the ratios $f, f'/\Lambda$ and on m_* . For excited electrons a limit beyond \sqrt{s} can also be obtained by looking at the reaction $e^+e^- \rightarrow \gamma\gamma$, which is sensitive to virtual e^* exchange in the t-channel in addition to the SM contribution.⁸ L3⁹ and OPAL¹⁰ have published results up to the highest energies, while DELPHI results are still preliminary¹¹. A preliminary combination of DELPHI and OPAL data was performed in 2001¹, and a new one should be available soon. No excess above the SM background was observed and upper limits for the single production cross sections and the f, f' couplings divided by the compositeness scale were derived assuming a model with an excited doublet with L,R components (pair production allows excited leptons with masses below 95-103 GeV to be excluded, for any coupling). Figure 2 (left) shows the limits obtained by OPAL for f/Λ vs m_{e^*} assuming $f = f'$.¹⁰ Figure 2 (right) shows the preliminary limits obtained at LEP (directly by DELPHI and OPAL, indirectly by all four experiments) for the excited electron assuming $f = f'$ ¹: they are compared with the limits obtained at HERA and at the Tevatron¹². For masses below 200 GeV they will remain the best limits for some time, until HERA exceeds an integrated luminosity of $\sim 1 \text{ fb}^{-1}$. In addition, HERA can search only for e^* and ν_e^* .

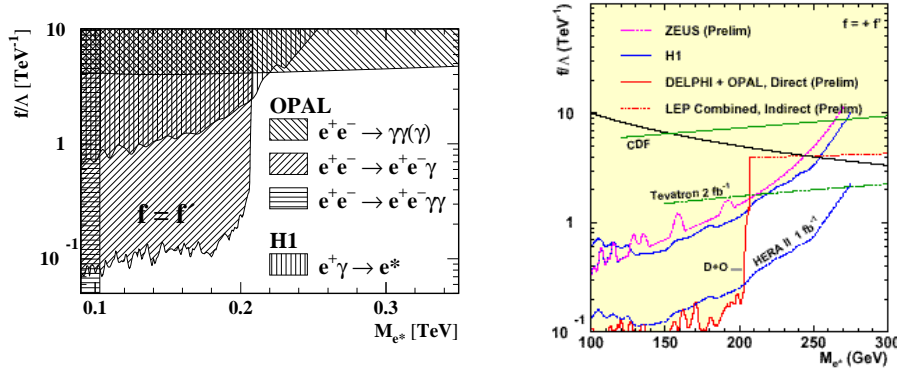


Figure 2: Left: 95% CL area excluded by OPAL data in the search for e^* : the limits from pair and single production, and the indirect limit are shown separately. The limits obtained by H1 at HERA are also shown. Right: DELPHI and OPAL combined search for e^* ; the indirect limit from $e^+e^- \rightarrow \gamma\gamma$ results from the combination of the four LEP experiments. The decreasing curve shows the hyperbola $f/\Lambda = 1/m_{e^*}$: $m_{e^*} > 248 \text{ GeV}$, for $f = 1$, $\Lambda = m_{e^*}$. Limits and sensitivities of HERA and Tevatron experiments are also shown.

4 Search for extra dimensions

As $m_{ew} \ll m_{Pl}$, unification of gravity with other forces could only take place at extremely high energies, well out of the reach of particle accelerators. Various solutions of the hierarchy problem have been proposed, which involve the existence of extra spatial dimensions (large ED, warped ED, etc.). These solutions can be tested at present accelerators and at the LHC.

4.1 Large extra dimensions

The ADD model¹³ assumes a D dimensional space-time, with $D = 3+n+1$, n being the extra space dimensions: SM fields live in a 3-dimensional rigid brane, whilst gravity is allowed propagate in the bulk, thus becoming diluted in the big extra space. If the n extra dimensions are

compactified on a torus (flat ED), one has $m_{Pl}^2 \sim R^n M_D^{n+2}$, with M_D the D-dimensional Planck mass, and if M_D is ~ 1 TeV, thus eliminating the hierarchy problem, the compactification radius would be $R = 0.3$ mm, 10 pm, 30 fm for $n\text{-dim} = 2, 4, 6$, respectively. The bulk graviton is expanded in a Kaluza-Klein tower of massive states, with $\Delta m \sim 1/R$, forming almost a continuous spectrum and being weakly coupled. At LEP one can look for i) graviton emission in $e^+e^- \rightarrow \gamma G$, i.e. γ +missing energy, ii) graviton exchange in boson and fermion pair production, $e^+e^- \rightarrow \gamma\gamma, WW, ZZ, f\bar{f}$. Experimentally, $n=1$ is excluded by the behaviour of Newton's law at solar system scales. Contrary to ew and strong forces, which have been tested down to $\sim (100 \text{ GeV}/c)^{-1} \sim 10^{-15}$ mm, gravity so far has been tested down only to the 0.1 mm scale, whilst improved experiments could decrease this limit by an order of magnitude. Limits on ED for $n = 2$ can also be derived from astrophysical and cosmological arguments¹⁴, but tend to be less constraining for larger n .

i) Graviton emission. The angular distribution for $e^+e^- \rightarrow \gamma G$ is peaked at small E_γ and θ_γ , and one of the principal SM backgrounds is $e^+e^- \rightarrow \nu\bar{\nu}\gamma$. The combination of the DELPHI and L3 single γ energy spectrum is shown in Fig. 3 (left). No deviation is observed with respect to the SM background. The exclusion limits for M_D as a function of n are presented in Fig. 3 (right): the ALEPH data have been included reconstructing the likelihoods from the fitted M_D vs n . OPAL data at the highest energies have not been yet analysed. For $n = 2, 3, 4, 5, 6$ one has $M_D > 1.60, 1.20, 0.94, 0.77, 0.66$ TeV.¹ The limits from CDF and D0 at the Tevatron are also shown: they equal the LEP limits only at large n .

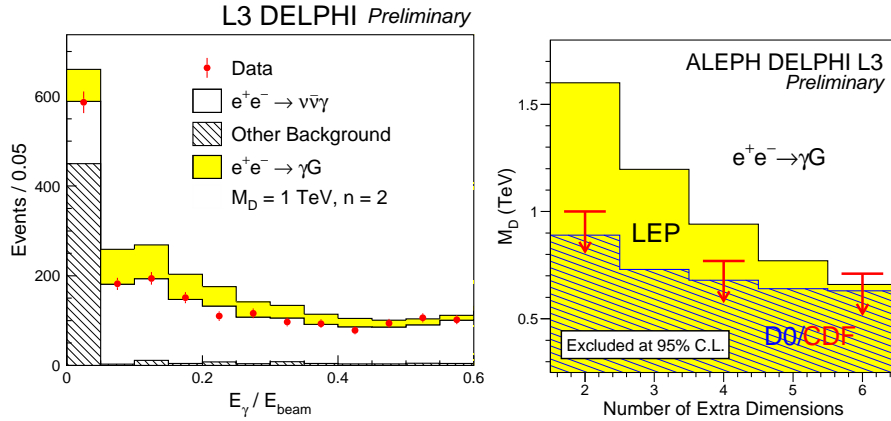


Figure 3: Left: photon energy spectrum in single γ events. Right: the limits on M_D as a function of the number n of extra dimensions.

ii) Graviton exchange. The most sensitive channel is Bhabha scattering. The scale is not the same as M_D but one has to introduce a cut-off, M_S , with $M_D^4 = (2/\pi\lambda) M_S^4$, $|\lambda| \sim 1$. Three terms contribute to the angular distribution, the SM term, G exchange and the interference term ($\sim \lambda/M_S^4$). No deviation from the SM predictions is observed and typical limits are $M_S > 1.20(1.09)$ TeV for $\lambda = +1(-1)$ at 95% CL combining the data from the four experiments.¹⁵ Similarly, the combined LEP results from $e^+e^- \rightarrow \gamma\gamma$ are $M_S > 0.93(1.01)$ TeV for $\lambda = +1(-1)$.⁸

4.2 Search for branons

If the brane is permitted to vibrate (instead of being rigid as in the ADD model), there will be brane fluctuations along the ED, and associated new pseudoscalar particles (branons, $\tilde{\pi}$) will appear. Branons could be dark matter candidates in low-tension brane worlds¹⁶. The search at LEP was performed by L3,¹⁷ complementing the search for G emission. In fact, if f (the brane tension) $\gg M_F$ (the gravity scale), then G is accessible first; if $f \ll M_F$, then one should look

for $\tilde{\pi}$ produced in pairs, $e^+e^- \rightarrow \tilde{\pi}\tilde{\pi}\gamma$ or $\tilde{\pi}\tilde{\pi}Z$, looking at events with photons/jets and missing energy. Since no excess is observed above the SM background, L3 sets a limit $M > 103$ GeV at 95% CL on the branon mass for an elastic brane ($f \rightarrow 0$), and $f > 180$ GeV ($M=0$)¹⁷.

4.3 Search for the radion

In the Randall-Sundrum (RS) model¹⁸ there are two branes: the SM is confined on one brane and gravity is concentrated on the other. One extra dimension with a “warped” geometry is allowed to fluctuate, resulting in a massive scalar, the radion, in addition to massless (gravitons) and massive (accessible at future colliders) spin-two excitations. Gravity in the RS model is weak because it is exponentially damped by the distance between the branes. The radion has the same quantum numbers as the Higgs (but the radion can couple directly to gluons), and Higgs-radion mixing is possible. OPAL¹⁹ has looked at the “Higgs/radion-strahlung” process, $e^+e^- \rightarrow Z + h/r$, reusing three searches for the Higgs boson. The excluded RS parameter space is obtained by a parameter scan ($m_r, m_h, \Lambda_W \sim 1$ TeV, mass scale on the SM brane, ξ , mixing parameter). For $\xi = 0$ the SM Higgs mass limit is reobtained, for $\xi \neq 0$ the mass limit is generally lower and decreases with decreasing Λ_W . For all ξ , $m_r, \Lambda_W \geq 246$ GeV, OPAL obtains $m_h > 58$ GeV at 95% CL,¹⁹ the analyses losing their sensitivity for $\Lambda_W \simeq 0.8$ TeV.

5 Conclusions

No evidence for single top production, excited leptons, or extra dimensions was found at LEP2 and exclusion limits were set. In many cases these results, four years after the LEP shut down, are still competitive with the new analyses produced at HERA and at the Tevatron.

Acknowledgments

I would like to thank the colleagues who helped with the preparation of this talk: W. Adam, S. Ask, L. Bellagamba, V. Hedberg, G. Paztor and P. Wells.

References

1. <http://lepexotica.web.cern.ch/LEPEXOTICA/>
2. V. F. Obraztsov, S.R. Slabospitsky and O.P. Yushchenko, *Phys. Lett. B* **426**, 393 (1998)
3. A. Heister *et al.*, ALEPH Coll., *Phys. Lett. B* **543**, 173-182 (2002)
4. J. Abdallah *et al.*, DELPHI Coll., *Phys. Lett. B* **590**, 21-34 (2004)
5. P. Achard *et al.*, L3 Coll., *Phys. Lett. B* **549**, 290-300 (2002)
6. G. Abbiendi *et al.*, OPAL Coll., *Phys. Lett. B* **521**, 181-194 (2001)
7. K. Hagiwara *et al.*, *Z. Phys. C* **29**, 115 (1985); F. Boudjema *et al.* *Z. Phys. C* **57**, 425 (1993)
8. <http://lepewwg.web.cern.ch/LEPEWWG/photons/welcome.html>
9. P. Achard *et al.*, L3 Coll., *Phys. Lett. B* **568**, 23-34 (2003)
10. G. Abbiendi *et al.*, OPAL Coll., *Eur. Phys. J. C* **26**, 331 (2003)
11. W. Adam *et al.*, DELPHI 2004-024-CONF-699, submitted to ICHEP04
12. E. Perez, *Int. J. Mod. Phys. A* **19**, 822 (2004)
13. N. Arkani-Hamed, S. Dimopoulos and G. Dvali, *Phys. Lett. B* **429**, 263 (1998)
14. S. Eidelman *et al.*, *Review of Particle Properties*, *Phys. Lett. B* **592**, 1 (2004)
15. <http://lepewwg.web.cern.ch/LEPEWWG/lep2/summer2002/Welcome.html>
16. A. Dobado, talk at this conference.
17. P. Achard *et al.*, L3 Coll., *Phys. Lett. B* **597**, 145-154 (2004)

18. L. Randall and R. Sundrum, *Phys. Rev. Lett.* **83**, 3370 (1999); ibidem, **83**, 4690 (1999)
19. G. Abbiendi *et al.*, OPAL Coll., CERN-PH-EP-2004-041, submitted to *Phys.Lett.B*